QWIPs enhance infrared detection

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Using sophisticated epitaxial growth techniques, it is possible to fabricate new forms of active devices with 'tailor made' characteristics that rely on the ability to engineer the electronic band structure of semiconductors on a nanometre scale. This article gives an example of the technique of bandgap engineering which can be used to create a new type of infrared detector based on III-V semiconductors.

Methods of detection of infrared (IR) radiation have been investigated for almost 200 years, since the astronomer William Herschel discovered what is now called the IR portion of the spectrum in 1800 [1]. IR detectors have been key components in thermal imaging, guidance, reconnaissance and communication systems.

The use of IR detectors for the military is well-known, and amply demonstrated in the Persian Gulf region where the IR imaging sensors for missile and surveillance systems have been vital to the operations. All important applications of IR techniques, both for military and civil purposes, rely on the detection of radiation in the 1-3 μm, 3-5 μm and 8-14 μm spectral range (the so-called atmospheric windows). The 8-14 μm wavelength region is especially important for imaging because the temperature of the human body and the environment is around 300 K, corresponding to a peak wavelength of thermal radiation of about 10 μm. The materials that cover the above wavelength regions include II-VI, III-V and IV-VI compound semiconductors.

With respect to the well-known HgCdTe detectors, GaAs/AlGaAs quantum well devices have a number of potential advantages, including the use of standard manufacturing technology based on advanced GaAs growth and processing techniques, highly uniform and well-controlled molecular beam epitaxy (MBE) growth on large GaAs wafers, high yield, greater thermal stability, and intrinsic radiation hardness.

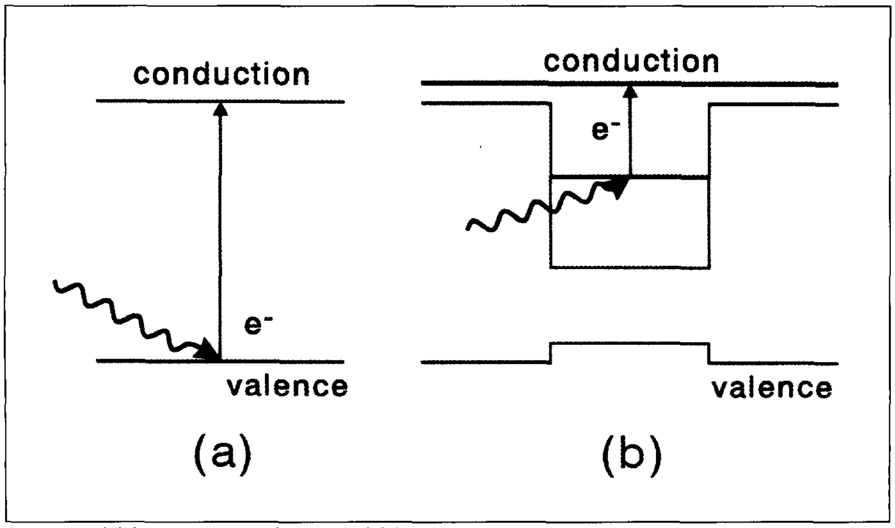

Figure 1. (a) Interband transition and (b) intersubband transition.

QWIP operation

The major physical mechanism of photodetectors is the absorption of photons, which changes the electric properties of the electronic system such that a photocurrent or photovoltage is generated. The performance of a photodetector depends on the optical absorption process, the carrier transport and the interaction with the circuit system.

Progress in IR detector technology is mainly associated with semiconductor IR detectors. These belong to the class of photon detectors where the radiation is absorbed within the material by interaction with electrons bound to lattice atoms or impurity atoms, or with free electrons. The electrical output signal that results from this interaction is due to the modified electronic energy distribution. Depending on the nature of interaction, the class of photon detectors is further subdivided into different types, including intrinsic, extrinsic, photoemissive and quantum well (QW) detectors.

The difference between quantum well IR photodetectors (QWIPs) and most other photodetectors is the type of electronic transition (see Figure 1) that creates electron-hole pairs. In the interband process an electron may be raised from the valence band to the conduction band, where the energy gap is E_g, by the absorption of a photon of frequency ν, provided that $h\nu > E_g$. In a QWIP, the process involves an intersubband transition where the absorbed IR radiation excites electrons bound in the quantum well into the continuum of states. In fact, there are four basic QWIP designs involving various transitions (see Figure 2). All these designs have been patented.

A schematic diagram of the conduction band in a bound to continuum QWIP under an applied voltage is shown in Figure 3. The structure containing many QWs for appreciable absorption is sandwiched between heavily doped, thick GaAs layers to which ohmic contacts can be made. The substrate is usually semi-insulating and fairly transparent between 1 μm and 20 μm. Absorption of long-wavelength IR photons can excite electrons from the state of QWs into the extended continuum states above the top of the barriers, thus producing a photocurrent. The performance of such a photodetector is determined by its responsivity, dark current and noise.

Brief history

L. Esaki and H. Sakaki [2] were the first to suggest the possibility of using the intersubband transition in GaAs/AlGaAs multi-quantum wells (MQWs) to detect IR radiation. This idea was investigated experimentally by J. Smith and his co-workers [3] at the California Institute of Technology in 1983. In 1985, West and Eglash at Stanford University [4] observed a strong intersubband absorption for the first time in a 50-period highly doped GaAs/AlGaAs MQW. The first working device based on QW photodetection was demonstrated in 1987 by Levine and his colleagues [5] at AT&T Bell Labs, New Jersey, USA. The QWIP device was based on the intersubband between two bound QW states and operated at λ = 10.8 μm. Since then the interest in QWIPs has increased continuously driven by promising applications, some of which are illustrated in the following sections. More details on QWIPs are given in the review by B.F. Levine [6].

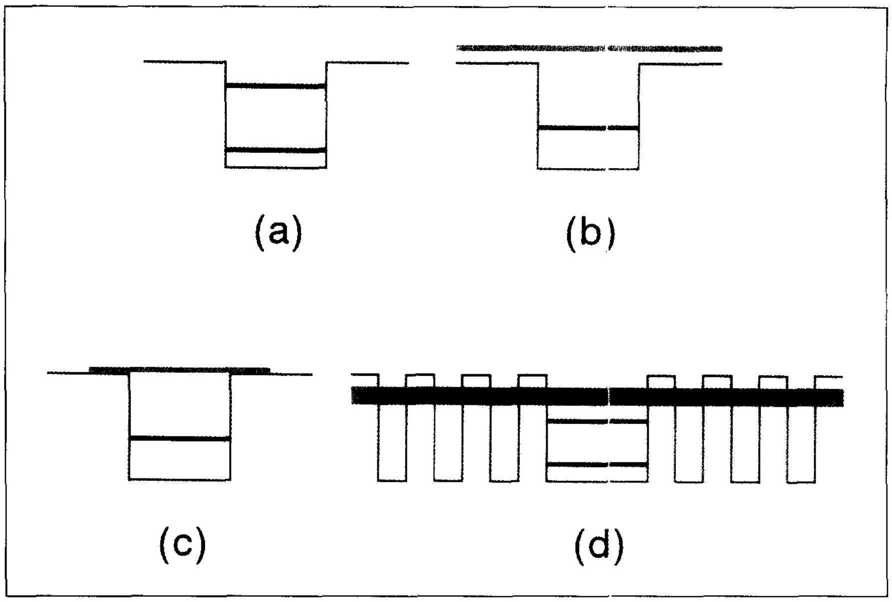

Figure 2. QWIP design transitions: (a) bound to bound, (b) bound to continuum, (c) bound to quasi-bound, and (d) bound to mini-subband.

There is growing interest in the possibility of integration of QWIPs with other devices, such as light-emitting diodes (LEDs), heterostructure bipolar transistors (HBTs) and field effect transistors (FETs) and the combination of several QWIPs grown within the same structure.

Several groups have explored the use of QWIPs grown one on top of the other for the purpose of achieving voltage-tunable multi-colour detection. H.C. Liu *et al.* [7] succeeded in achieving three-colour detection in a QWIP stack with three QWIPs turning on sequentially with increasing peak detection wavelength as the bias voltage across the device increased. Three well-resolved peaks were observed at 7.0, 8.5 and 9.8 μm, which could be independently selected by adjusting the bias voltage. The multi-colour QWIP capability was expanded by K.L. Tai *et al.* [8] and Y.H. Wang *et al.* [9].

Recent achievements

Recently, L.C. Lenchyshyn *et al.* [10] proved that the behaviour of the stacked devices corresponds to the individual detectors simply acting in series with each other. The critical characteristics of the individual QWIPs were identified as the dependence of the photocurrent and the dynamic resistance on the dark current. The switching-on of the photocurrent was found to be determined primarily by the QWIP peak detection wavelength.

The integration of a QWIP with an LED was first proposed by V. Ryzhii *et al.* [11] and realized by H.C. Liu *et al.* [12] in 1995. The operation of such devices is based on direct injection of carriers photoexcited in the QWIP by mid- or far-IR (MIR or FIR) radiation into the LED active region, and subsequent emission of near-IR (NIR) radiation. Therefore, a QWIP-LED operates as a converter of MIR and FIR to NIR radiation, or as a QWIP with optical output. These NIR photons are then directed towards a charge coupled device (CCD) camera where the up-converted image of the IR object is formed and detected. The technological importance of the QWIP-LED is that it allows fabrication of large two-dimensional focal plane arrays (FPAs) with NIR output which can be easily integrated by well-developed devices such as Si CCDs.

L.B. Allard *et al.* [13] recently used the idea that an FPA consisting of a large number of separated pixels can be replaced by one large area QWIP-LED (this is due to the

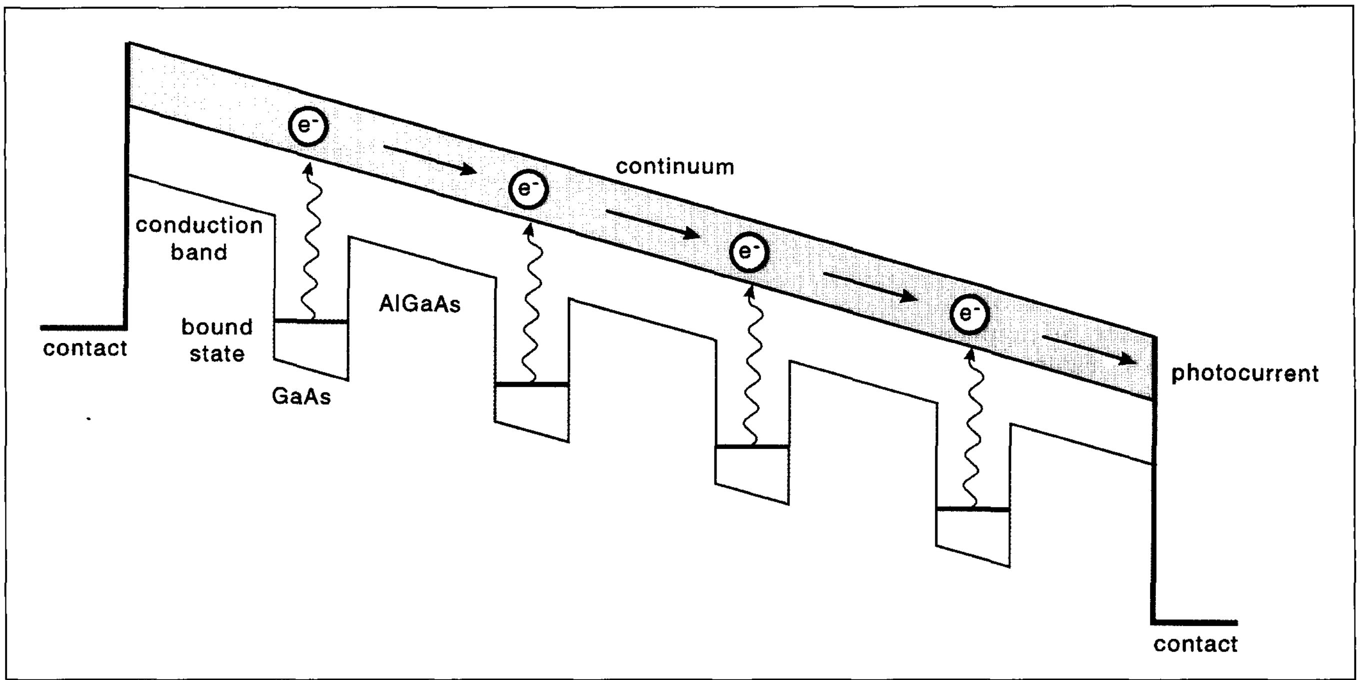

Figure 3. Schematic band diagram of a GaAs/AlGaAs QWIP showing the processes for photo-excitation and relaxation that control the photocurrent.

fact that the input MIR and FIR image and output NIR image are spatially correlated, i.e. in the plane of the device) to realize a pixel-less IR imaging device. QWIP-LED integration has definitively opened up new prospects for IR imaging devices.

IR imaging systems that operate in the very long wavelength IR region (12-18 μm) are required in many space applications such as monitoring the global atmospheric temperature profiles, cloud characteristics and relative humidity profiles, etc. which are planned for NASA's Earth observation system [14]. S.D. Gunapala *et al.* [15] reported recently the development of a very sensitive, very long wavelength IR GaAs/AlGaAs QWIP based on a bound-to-quasi-bound intersubband transition, and demonstrated a 15 μm cutoff 128x128 FPA imaging camera. They achieved excellent imaging with a noise equivalent differential temperature of 30 mK.

Although the principal work has been carried out using GaAs/AlGaAs, QWIPs have also been reported using other material systems such as InP/InGaAs(P) [16], GaAs/InGa(As)P [17] and InGaAs/InAlAs [18]. Very recently C. Jelen *et al.* [19] reported new results for n-type GaAs/GaInP QWIPs with cutoff wavelength greater than 10 μm. It is therefore possible that integrated multispectral detectors with a photoresponse in both the 3-5 μm and 8-12 μm regions can be developed within the same GaAs/GaInP material system.

GaAs-on-Si substrate technology has promising advantages over GaAs bulk ICs such as higher thermal conduction, greater mechanical strength of substrates, and expansion of wafer size. Despite the large lattice mismatch inherent to growing GaAs on Si, D.K. Sengupta *et al.* [20] successfully used molecular beam epitaxy (MBE) to grow good quality GaAs/AlGaAs QWIPs on top of a metal organic chemical vapour deposition (MOCVD)-grown GaAs-on-Si substrate. The resulting detector structure exhibits dark current and absolute responsivity comparable to a similar detector structure grown on a GaAs substrate. These results are promising for applications in the important 8-12 μm atmospheric window.

Recently, Prof. M. Razeghi and her co-workers at the Center for Quantum Devices, Northwestern University, USA, reported the MBE growth and characterization of InAs/GaSb superlattices grown on semi-insulating GaAs substrates for long wavelength IR detectors. X-ray diffraction simulation has also been performed to verify the superlattice structures. Figure 4a shows good agreement between the X-ray diffraction spectra of the two 50 period superlattices and the simulated spectra. It also indicates excellent reproducibility and smooth interfaces. Photoconductive detectors fabricated from the superlattices showed 80% cutoff at 11.6 μm and peak responsivity of 6.5 $V.W^{-1}$, with Johnson noise limited detectivity of $2.36x10^9$ $cm.Hz^{1/2}.W^{-1}$ at 10.7 μm at 78 K (Figure 4b). The lower Auger recombination rate in this system provides comparable detectivity to HgCdTe detectors at 300 K, since the responsivity decreases by a factor of only 14 from 78 K to room temperature at 10.3 μm (Figure 4c). Higher uniformity over large areas, simpler growth and the possibility of having read-out circuits in the same GaAs chip are the advantages of this system over HgCdTe detectors for operation near room temperature.

QWIP devices are usually operated at cryogenic temperatures (77 K)

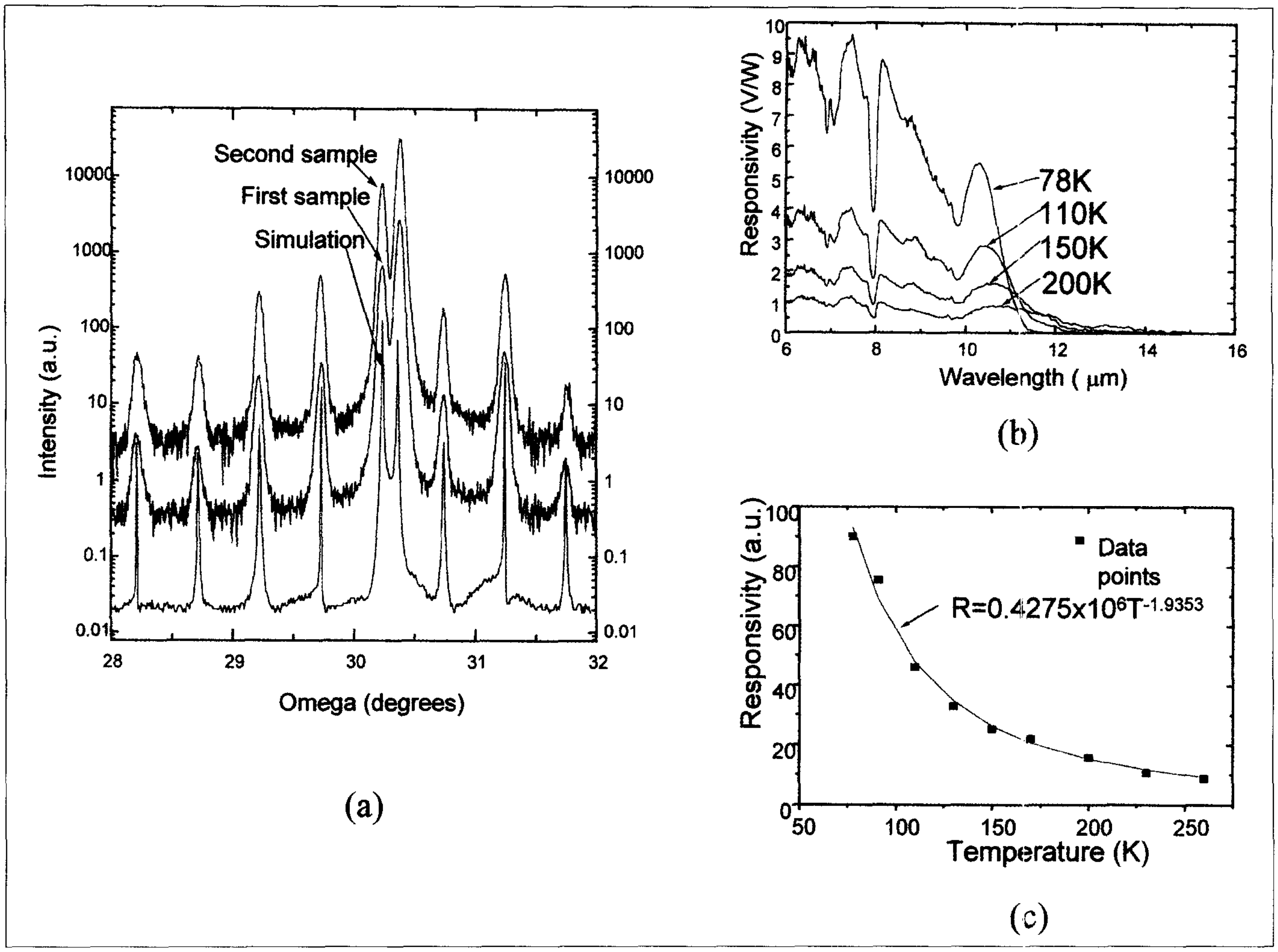

Figure 4. (a) High-resolution X-ray diffraction of two samples and the simulation result; (b) responsivity of the photoconductor in the 8-12 μm range at different temperatures; and (c) responsivity of the detector at 10.3 μm versus temperature. (Courtesy of Prof. M. Razeghi.)

because the dark current conductivity increases rapidly with temperature. In addition, under room temperature operation the application of an electric field across the active region causes problems. H. Schneider *et al.* (21) have investigated photovoltaic (PV) QWIPs which do not require the application of an external field. The PV QWIPs use detection concepts that rely on internal fields. The authors investigated the temperature-dependent properties and the room temperature temporal response of a PV QWIP. They showed that their detector is intrinsically fast, and demonstrated its use as an ultra-fast monitor detector for pulsed and continuous wave IR lasers. The device has a 50% cutoff wavelength of 10.5 μm at 77 K. The voltage responsivity, R_V at 76 K and 300 K was 620 V.W^{-1} and 7 mV.W^{-1}, respectively. Using a 2 picoseconds (ps) pulse from a free electron laser at an excitation wavelength of 10.2 μm, they measured rise and fall times of 8 ps and 63 ps, respectively.

Although QWIP devices are used in high-resolution thermal imaging, there are still problems with light coupling in small detector pixels. Several techniques, including diffraction gratings and random gratings, have been used to improve light coupling. These rely on light trapped within the device active regions. C.J. Chen *et al.* [22] have proposed a different light coupling scheme which uses total internal reflection instead of diffraction. The structure, which is called corrugated (C) QWIP, is ex-

Table 1. Detectivity of III-V QWIP detectors operating in the 8-14 μm wavelength range

Year	Peak response (μm)	Single element (S) or array (A)	Detectivity (cm.Hz$^{1/2}$.W^{-1})	Ref.
1990	8	S	4×10^{10} (77 K)	23
1991	9.0	S	1.8×10^{10} (77 K)	24
1992	8.3-10.7	S	$(2\text{-}10)\times10^{10}$ (77 K)	25
1993	9.5 (cutoff)	A (128x128)	3.2×10^{13} (40 K)	6
1994	8.1 (cutoff)	A (40 linear)	2.1×10^{10} (77 K)	26
1997	9	S	4.5×10^{10} (78 K)	2

pected to be free of the problems associated with conventional light coupling techniques. The C-QWIP consisted of an array of triangular prisms created by etching linear V grooves directly into the active detector region. A systematic study was performed on a C-QWIP with cutoff wavelength λ_c ranging from 5 to 17.3 μm, and device areas ranging from 50x50 μm^2 to 500x500 μm^2. It was found that the coupling efficiency was independent of both the detector wavelength and the pixel size. Furthermore, their results showed that the detectivity increased by a factor of 2.4 compared with devices with a standard 45° edge coupling. For λ_c = 9.4 μm, the peak detectivity at 78 K was 4.5×10^{10} $cm.Hz^{1/2}.W^{-1}$.

The performance of the QWIP detectors has continually improved since the first device was built in 1987. Table 1 shows the detectivity of the QWIPs operating in the 8-14 μm wavelength range. The detectivity, which is the signal-to-noise ratio normalized to unit area and unit bandwidth, is a figure of merit widely used to compare the performance of detectors.

Among the different types of QWIP photodetectors, the technology of GaAs/AlGaAs MQW detectors is the most mature. The strength of the GaAs/AlGaAs QWIP is that well-understood growth and processing methods are available and new detector design ideas can be demonstrated rapidly using the MBE technology.

QWIPs provide a new alternative technology for the detection of IR radiation with a wavelength greater than about 3 μm. QWIPs, especially large two-dimensional detector arrays, are well suited in terms of weight, size, cost and performance for applications in space.

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